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The summary of the equipment acquisitions under the University Research Instrumentation Program, Grant AFOSR-86-0225 effective 1 Aug 86 to 31 Jul 88. The purpose of this program has been to provide modern plasma sources and data acquisition capability for the ongoing research program on Fundamental Processes in Partially Ionized Plasmas, supported by the Air Force Office of Scientific Research. In particular, under this Grant Stanford has acquired, installed, and characterized a 50kW induction plasma torch system and associated diagnostice, and has modernized the data acquisition capability through micro-computer systems. This new equipment has had a very favorable effect on the experimental capability and has already contributed to the research output.

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on

FUNDAMENTAL PROCESSES IN PARTIALLY IONIZED PLASMAS

University Research Instrumentation Program

Grant AFOSR-86-0225

Prepared for

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

For the Period

August 1, 1986 to July 31, 1988

Submitted by

C. H. Kruger, Principal Investigator

August 1988

HIGH TEMPERATURE GASDYNAMICS LABORATORY
Mechanical Engineering Department
Stanford University

Final Report

on

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INTRODUCTION

This report summarizes the equipment acquisitions and research results under the University Research Instrumentation Program, Grant AFOSR-86-0225 effective 1 August 1986 to 31 July 1988. The purpose of this program has been to provide modern plasma sources and data-acquisition capability for the ongoing research program on Fundamental Processes in Partially Ionized Plasmas supported by the Air Force Office of Scientific Research at the High Temperature Gasdynamics Laboratory of Stanford University.

This research program encompasses studies of the properties of partially ionized plasmas, discharge effects in plasmas, the interaction of discharges and fluid mechanics - particularly, MHD-induced secondary flows, and the diagnostics of partially ionized plasmas. Experimental work under this program had utilized existing plasma sources and data-acquisition capability which were installed years ago. The equipment acquired under the present URIP Grant has modernized and made more flexible the plasma-source and data-acquisition capability of the Laboratory for use in all aspects of the ongoing research.

In particular, under this Grant we have acquired, installed, and characterized a 50kW induction plasma torch system and associated diagnostics, and have modernized our data-acquisition capability through micro-computer systems. This new equipment has had a very favorable effect on our experimental capability and has already contributed to our research output, as evidenced by the publications noted in the last section of this report.

EQUIPMENT ACQUISITION AND RESEARCH

The equipment acquired under this URIP Grant was aggregated into two major systems for accounting purposes; a plasma torch system and associated diagnostics, and a data acquisition system. The final cost of the plasma system was $215,376 and that of the data acquisition system $24,276. In addition, $3,348 were expended for various set-up costs.

After a thorough investigation following our original proposal, it was decided that the most effective and flexible plasma source would be a TAFA Model 66 induction torch powered by a custom LEPEL 50 kilowatt RF power supply. This equipment, configured to our specifications, was ordered early in the term of the Grant and was delivered to our Laboratory near the end of the first year. We then provided 440V 3-phase power installation and the various cooling water connections, and TAFA and LEPEL field engineers completed the installation and commissioning of the torch at our Laboratory. Subsequently, we have performed a series of check-out and characterization experiments with the torch and have proceeded to research involving non-equilibrium effects on plasma properties. Figures 1 and 2 show the induction plasma torch in operation.

This induction torch provides a flexible source of plasmas at temperatures up to 10,000K, operating with a variety of gases and additives with an absence of electrode-generated impurities. The torch, being relatively large, provides for realistic conditions not dominated by wall effects but at the same time is compatible with university-scale research conducted by Ph. D. students. It is an excellent test-bed for the development of laser diagnostics of plasmas, for discharge studies, and for the studies of various nonequilibrium effects - including in particular the effects of nonequilibrium on reaction rates and plasma properties.

In addition to the torch itself, we have designed and tested three optical-quality quartz test sections and implemented laser and spectroscopic diagnostics for plasma measurements under controlled conditions. Figure 3 is a photograph of one of these test sections under torch operation.

In an extensive series of experiments we have confirmed satisfactory operation of the torch and power supply over a range of conditions. Our decision to purchase a commercial torch was motivated by the desire to move past these preliminary experiments as quickly as possible and to proceed with the other aspects of our research, and this was readily accomplished. Beyond this, we have now fully characterized the plasma, first at the exit of the torch itself and then downstream in the special quartz test sections. For example, we have measured the "Boltzmann" temperature based on the ratio of excited electronic state populations in argon and the "LTE" temperature based on absolute emission intensities, and interpreted the results in terms of non-equilibrium in so-called thermal plasmas, resulting from radiation escape. We have also made preliminary laser-induced fluorescence measurements with the torch operating on air, in anticipation of research on non-equilibrium effects on the properties of air plasmas.

To aid in the understanding of how nonequilibrium effects may have contributed to the significant discrepancy in the literature with regard to the radiation source strength in argon, we have recently measured the total radiation in the wavelength range 0.25 to 2.4 nm. using a sensitive pyroelectic detector. Our current results are shown in Figure 4, for plasma conditions at one atmosphere ranging from 7000K to about 9500K. These results suggest that the radiation source strengths of Miller and Ayen, which are often used in the modeling of inductively coupled plasmas, and for calculations related to thermal plasma chemistry, may significantly underestimate the importance of radiation losses. Also shown in Figure 4 are the earlier measurements of Emmons, Evans and Tanken, and Krey and Morris. Of these, only the data of Emmons overlap the present measurements. We believe that the order-of-magnitude difference at lower temperatures results from pronounced nonequilibrium effects in the earlier experiments of Emmons. The dashed line in Figure 4 is an upper-bound extrapolation of the data of Emmons from 10,000K, where Emmons, Evans, and Krey agree to within a factor of 2, to lower temperatures. This upper-bound is based on the fact that the measured radiation originates from energy levels of at least 13.1 eV, so that below 10,000K the radiation source strength should fall off at least as rapidly as a Boltzmann factor at 13.1 eV. Thus, the slower decay below 10,000K reported by Emmons appears to be anomalous.

The other aspect of this equipment program has been the modernization of our data-acquisition capability. Since the time of our proposal for this Grant, we experienced a major disk failure on the computer used for MHD data acquisition. The questionable reliability of that computer was the motivation for including data-acquisition instrumentation in our proposal. We have now reorganized that data-acquisition capability with equipment purchased under this Grant. The MHD flowtrain and the experiments on electron recombination in molecular plasmas, as well as the new plasma torch system, now have microcomputer control and acquisition systems which are regularly in use, and which have contributed substantially to the success of recent experiments.

In particular, our recent measurements of MHD secondary flow over a wide range of interaction parameters and our discovery of an apparent saturation in secondary flow effects with increasing interaction parameter would not have been possible without the new data-acquisition capability.

Publications made possible in part by the new equipment purchased under this Grant are listed in the following section.

PUBLICATIONS MADE POSSIBLE BY THIS EQUIPMENT GRANT

1. Girshick, Steven L. and C. H. Kruger, "Secondary Flow in a Linear MHD Channel with Applied Axial Current," 9th Int'l Conference on MHD Electrical Power Generation, Ibaraki, Japan, November 1986

2. Kruger, C. H. and R. C. Goforth, "New Measurements of Secondary Flow in an MHD Channel," 25th Symposium for the Engineering Aspects of Magnetohydrodynamics, Bethesda, MD, June 1987.

3. Kruger, C. H., "Nonequilibrium Effects in Thermal Plasma Chemistry," 8th Int'l Symposium on Plasma Chemistry, Tokyo Japan, August 1987.

4. Kruger, Charles H., "Nonequilibrium Effects in "Thermal" Plasmas: Radiation Transport and Chemical Reactivity," Sixth Symposium on Energy Engineering Sciences, Argonne, IL, May 1988.

5. Goforth, R. C. and C. H. Kruger, "Measurements of the Effect of Interaction Parameter and Wall Temperature on Secondary Flow in an MHD Channel," 26th Symposium on Engineering Aspects of Magnetohydrodynamics, Nashville, TN, June 1988.

6. Kruger, C. H., "Nonequilibrium Effects in Thermal Plasma Processing," 41st Annual *Gaseous Electronics Conference*, Minneapolis, MN, October 1988.

7. Kruger, C. H., "Nonequilibrium Effects in Thermal Plasma Chemistry," Submitted to Plasma Chemistry and Plasma Processing, June 1988.

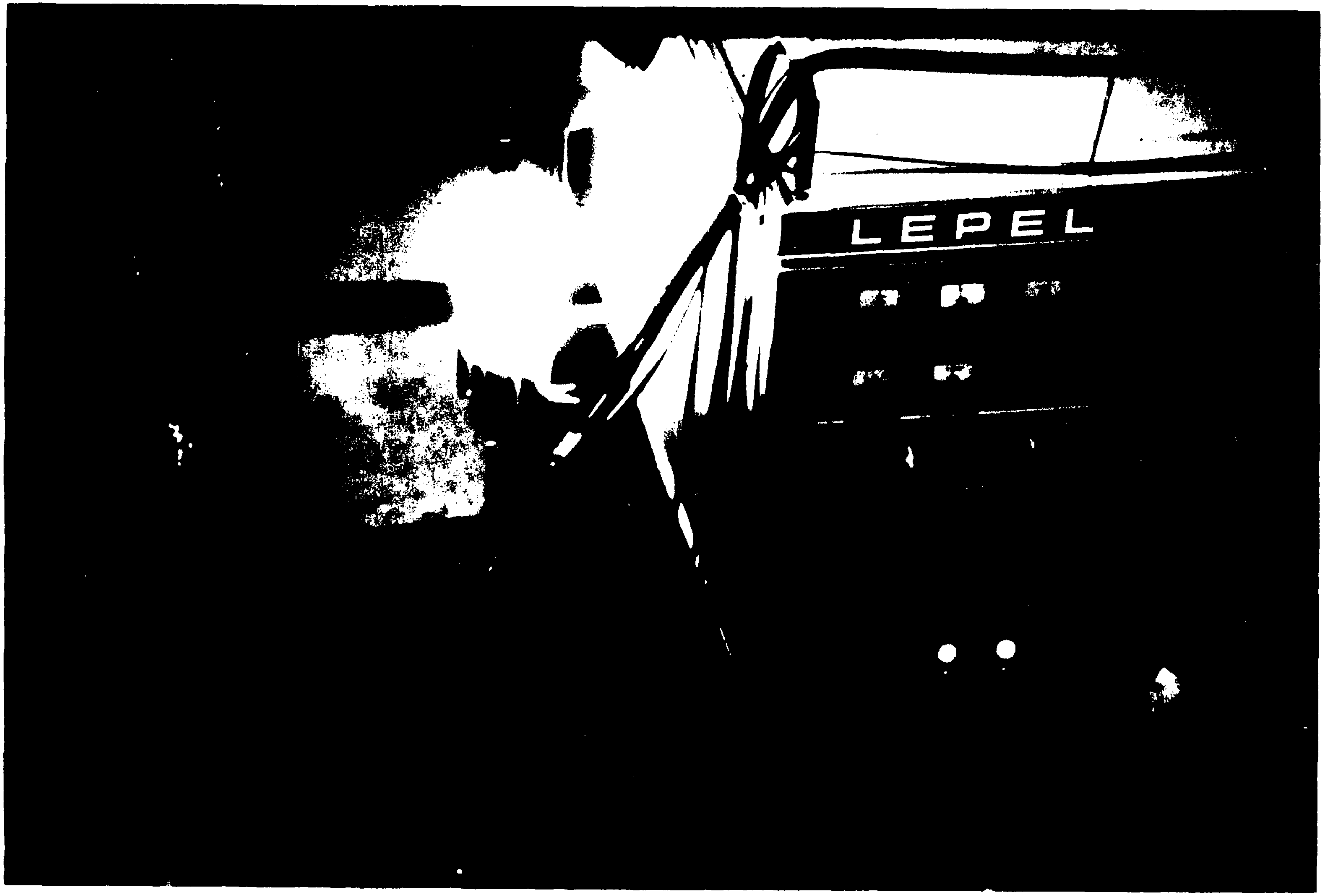

FIGURE 1: INDUCTION TORCH IN OPERATION

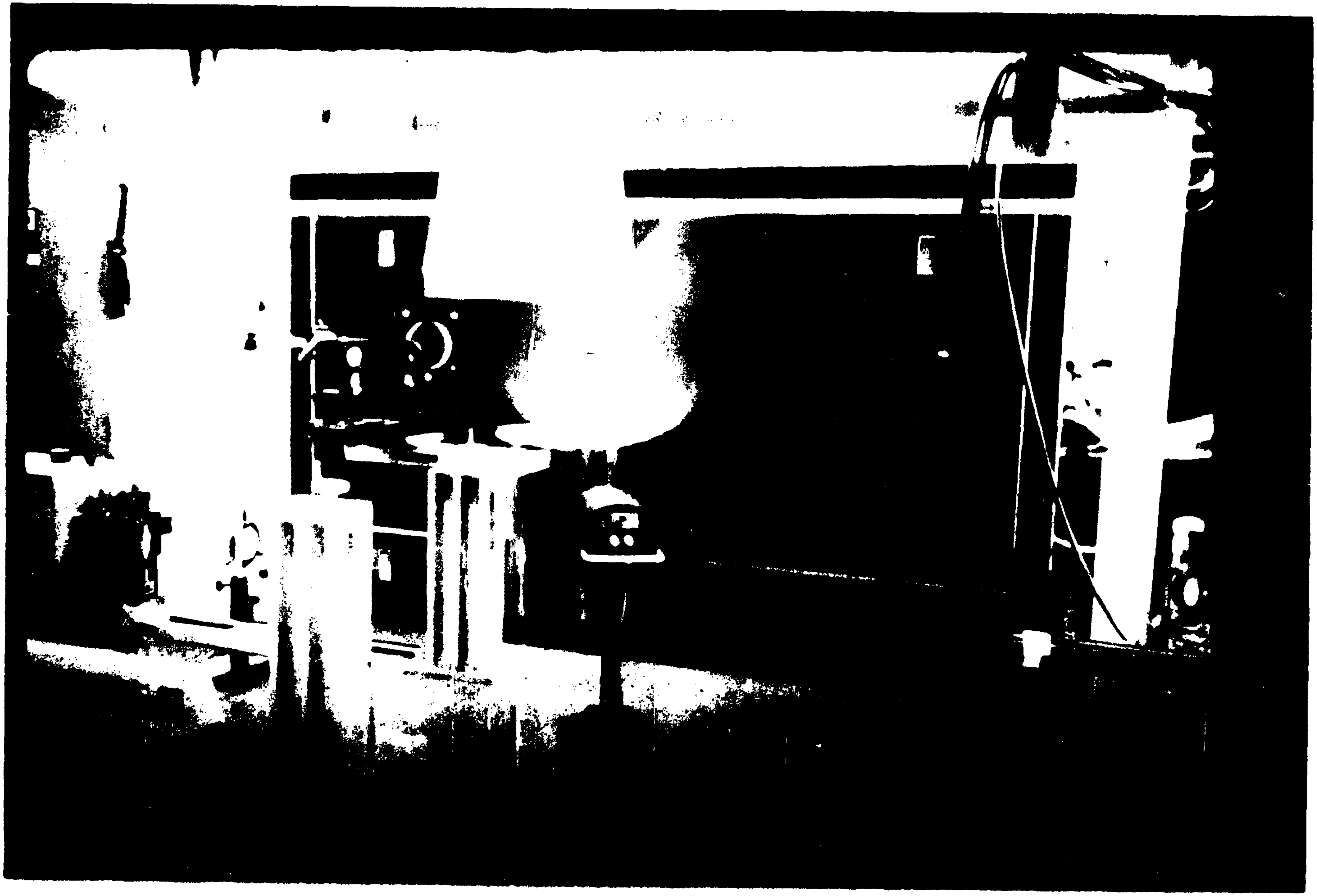

FIGURE 2: STANFORD PLASMA FACILITY

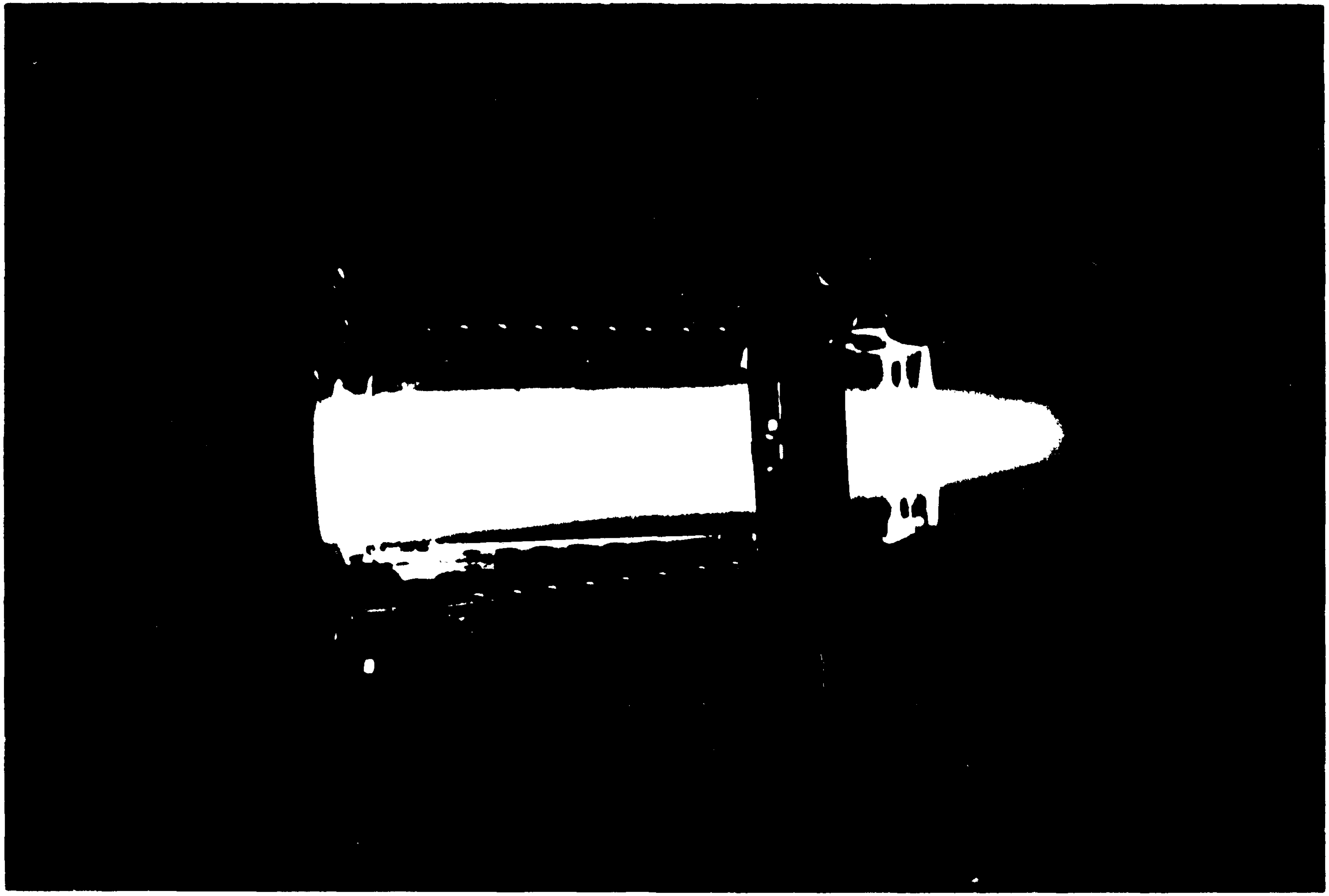

FIGURE 3: WATER-COOLED QUARTZ TEST SECTION

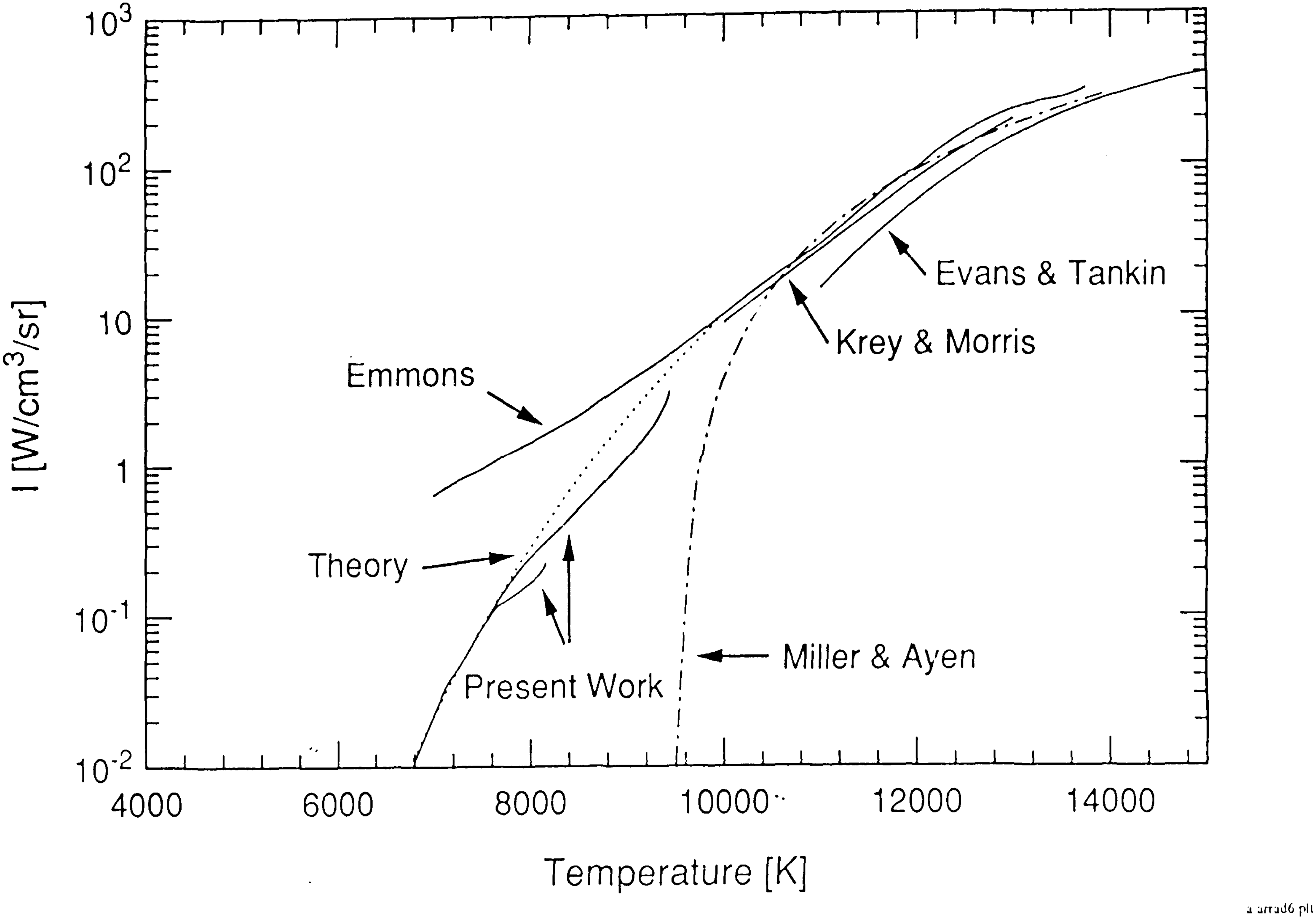

FIGURE 4: ARGON VOLUMETRIC RADIATIVE SOURCE STRENGTH